2014

Initial Investigation of Analytic Hierarchy Process to Teach Creativity in Design and Engineering

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Abstract

This paper discusses the importance of, and challenges to, including design creativity in undergraduate curriculum to engage and encourage students to think creatively in design and engineering. Investigators are exploring how and why the Analytic Hierarchy Process (AHP) method facilitates a creative process, overcomes obstacles to creativity and changes students' perceptions to explore creative design solutions. An AHP-based creativity process is developed and implemented in three different case studies. Lessons learned from these initial trials are discussed herein and will contribute to a detailed investigation to assess the effectiveness of the proposed AHP-based design process to foster an environment for engineering students to think creatively and to produce creative solutions.

1. Introduction

Engineers and STEM professionals must possess the skills and experience for original and critical thinking. As importantly, they must be able to incorporate creativeness in their design methodologies in order to be competitive in today's global market. There is an increasing demand to encourage and develop creativity in engineering and science classrooms.[1] Unfortunately, engineering educators are still struggling to develop an effective method to train and engage engineering students to be creative.[2] One major reason may be that engineering educators do not fully understand, nor are able to measure, creativity. Therefore, there is a need to develop an effective teaching methodology that incorporates the creativity process in the classroom to expand the student's knowledge and ability to think creatively in their design and engineering efforts. Engineers often use the term innovation alongside creativity. Innovation is generally understood as "the successful introduction of a new thing or method…new products, processes, or services".[3,4] In this study, innovation is referred to as the end product of a creative process. Therefore, innovation in this study is considered as a part of creativity.

This investigation takes a fresh look at using the Analytic Hierarchy Process (AHP) as the foundation for a new design process to engage and encourage students to think creatively in design and engineering. AHP is a structured decision-making methodology based on mathematics and psychology that was developed in the 1970s by Thomas Saaty. It has applications in individual decision-making, and has proven very effective in group settings, especially to solve complex problems in areas of business management, manufacturing, engineering, educational, political, and social applications.[5] This paper explores how the AHP method facilitates a creative process by overcoming obstacles to creativity and enabling students to explore creative design solutions. The classical AHP is discussed to give the reader an understanding of the methodology. Previous design creativity methods are reviewed. The proposed AHP-based design process is presented in detail and is implemented in the classroom using three different case studies. These case studies include: the design of a concept robotic boat; the design of the navigation strategy of the robotic boat; and the design of a website. Results and lessons learned from these diverse case studies are reported. Finally, the authors outline suggestions for future improvement and assessment of the proposed AHP-based design process for teaching creativity to engineering students.

2. Need for Creativity in Engineering Curriculum

Dym et al.[6] defined engineering design as "a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints." Though creativity is not specifically mentioned, the above definition of engineering design is equivalent to that provided by Meyer, "... creation of new and useful products including ideas as well as concrete objects".[7] Piffer recommended a framework made of three elements; novelty, appropriateness or usefulness and impact to define and measure creativity.[8] The factor "impact" is added in order to measure the social and cultural influence of the design. In Piffer's definition, creativity implies creative achievements that include both product creativity and personal creativity. Personal creativity is different from the former, which is the total sum of product creativity that a person can generate. Piffer argued that to achieve creative production the application of convergent thinking, knowledge and analytical thinking are all as important as divergent thinking. Therefore, divergent thinking alone cannot be used to measure creativity. Divergent thinking is usually scored by fluency, flexibility, novelty and elaboration. Fluency refers to both the number of ideas and the variation in idea types. Of note, the revised Creative Engineering Design Assessment (CEDA) tool uses fluency, flexibility, originality (novelty) and usefulness to measure engineering creativity.[9] Fluency and flexibility are means to measure one's ability in problem finding while novelty and usefulness measure one's ability in problem solving. Problem solving is specifically required to engineer a creative product. Charyton et al. [9] considered one's problem finding ability as a measure of divergent thinking and one's problem solving ability as a measure of convergent thinking.

One shortcoming of existing engineering curriculums is that the majority emphasizes the development and refinement of problem solving skills rather than problem finding skills. This is because the former is much easier to organize, teach and assess than the latter. The learner-centered approach has been introduced into the engineering curriculum to encourage divergent and convergent thinking and includes interdisciplinary hands-on, open-ended and team-based project activities.[10] Immersive environments, computer-aided design and visualization tools, as well as real-world projects, have also been introduced into the classroom to help students to formulate the design problem and create, visualize and analyze design alternatives.[10,11]

Dym et al. outlined five dimensions that constitute skilled design thinking: divergent-convergent thinking, thinking as designing systems, making design decisions, thinking in a team environment and using engineering design languages.[6] The latter includes verbal/textual statements, graphical representations, shape grammars, mathematical or analytical models and numbers.[12] The semantic coherence of oral and written histories of a design cycle as well as the breadth and the depth of design sketches also have a positive impact on the design outcome.[13]

Baillie[1] and Liu and Schonwetter[4] structured a creative process into five phases: preparation, generation, incubation, verification, and evaluation. Note that the creative process referenced here is a development procedure for creative production, which is different from that mentioned in Piffer.[8] The latter placed the creative process in the realm of cognitive psychology.

3. AHP Decision Making Process

The AHP is a structured, multi-criteria decision-making methodology based on mathematics and psychology that was developed in the 1970s by Thomas Saaty. Through this process, the decision problem is viewed as a system which can be broken down into smaller subsystems consisting of key criteria for decision making.[14] One of the most important tasks is to define the elements within the system that need to be included in the decision process. A sufficient amount of data should be analyzed, taking great care not to make the problem too complex. Once the elements are chosen, the system is then arranged in a hierarchical structure consisting of various levels of subsystems. The top level of the hierarchy is the objective or primary goal of the process. The bottom level consists of the alternatives available in reaching that goal. Between the top and bottom levels lie the criteria and sub-criteria (possibly multiple) levels. Once the hierarchy is created, the next step in the AHP is to determine the degree to which elements on one level of the hierarchy influence the element on the level above it. For each of criterion, the associated sub-criteria are examined to derive their strengths of importance or priority on the criterion. Each of these examinations will be considered as an assessment, which will produce a $n \times n$ comparison matrix, C, to represent the relative strengths, or priorities among the n sub-criteria. Each row and each column of the comparison matrix correspond to a specific sub-criterion. The value of $C(i, j)$ quantifies the relative importance of the criterion in Row i to the one in Column j based upon the fundamental scale outlined by Saaty for pairwise comparison and shown in Table 1.[14]

Table 1. Pairwise Comparison Scale [14]

Intensity of Importance	Definition
1	Equal importance
3	Slightly more important
5	Essential or strong importance over another
7	Very strong importance over another
9	Extreme importance
2,4,6,8	Intermediate values of two adjacent judgments

For example, if the criterion i is found to be "slightly more important" than the criterion j, a value of 3 is then assigned to $C(i, j)$. Note that the reverse comparison yields a reciprocal relation, as shown in Eqn 1.

$$C(j,i) = (1/C(i,j)) \tag{1}$$

Next, a column vector, known as the priority vector, $\boldsymbol{p}$, is determined. It can be set as the right eigenvector corresponding to the maximal eigenvalue of the pairwise comparison matrix C matrix; e.g., $C\boldsymbol{p} = \lambda_{\max}\boldsymbol{p}$. Alternatively, an element in $\boldsymbol{p}$ can be set as the geometric mean of a row of C. That is, the i^{th} element of $\boldsymbol{p}$ can be calculated as:

$$p_i = \sqrt[n]{\left(\prod_{j=1}^{n} C_{ij}\right)} \quad (2)$$

The value of p_i represents the relative strength of influences of sub-criterion i among n sub-criterion on the corresponding upper level criterion. This procedure is done for each criterion and sub-criterion matrix until it reaches the lowest level of the hierarchy, which is the collection of all decision alternatives.

The final step in the AHP is to establish the total global score. This is done by combining the normalized local priority weights of the alternatives, sub-criteria and criteria levels through successive multiplication. That is, the weights at the lowest level are multiplied with respect to all successive upper levels in the hierarchy. The new composite weights are normalized; the magnitude indicates the relative preference of the decision alternative. The decision alternative that receives the highest value reflects the optimal alternative.

Every step in the AHP process can involve a group of decision makers. Each of the stakeholders can select the objective, the decision criteria and the alternatives and establish his or her own pair-comparison tables and associated priority vectors. The latter can be aggregated by using the method of geometric mean to make group rankings.[15] For example, set the priority vectors as $\boldsymbol{q}_k$, $k = 1$ to m, produced either individually or by a group of m decision makers, based upon Eq. (1). The priority vector that represents the aggregated group ranking is given by Eqn 3, where i corresponds to the i^{th} criteria in the associated pairwise comparison table.

$$p_i = \sqrt[m]{\left(\prod_{k=1}^{m} q_{ik}\right)} \quad (3)$$

Although the AHP is designed to minimize inaccuracies, judgment errors due to bias and lack of knowledge can be introduced in preparing the comparison matrix. By definition, the elements in C have to satisfy the following condition to be called consistent, for a k that is different from i and j, as shown in Eqn 4.

$$C(i, j) = C(i, k) \times C(k, j) \quad (4)$$

The maximal eigenvalue of a perfectly consistent comparison matrix C is exactly equal to n, the number of criteria in C. Therefore, the deviation between $\lambda_{\max}$ and n is used as a measure of inconsistency and is referred to as the consistency index (CI), shown in Eqn 5.

$$\mathrm{CI} = \frac{(\lambda_{\max} - n)}{(n-1)} \quad (5)$$

The ratio of the consistency index (CI) to the average random index (RI) is called the consistency ratio and is used to collectively measure the judgment errors in constructing each comparison matrix, *C*. The average random index (RI) is simply the consistency indices of randomly generated comparison matrices. The consistency ratio of any comparison table must be less than 10% to be considered acceptable.

4. AHP to Facilitate Creativity: Using C-K Theory

The structured process of AHP lends itself to provide a comprehensive and rational framework for structuring a decision problem, for representing and quantifying its elements, for relating those elements to overall goals, and for evaluating alternative solutions. It has unique advantages in that it reduces personal biases and fears, allows for the comparison of dissimilar alternatives, and overcomes challenges where communication among team members may be impeded by their different specializations, terminologies, or perspectives. AHP's strength lies in its impartial and logical grading system. AHP also has the ability to handle a mixture of qualitative and quantitative criteria.[16]

As a group decision making tool, AHP is structured to encourage team dynamics. Each of the team members has the opportunity to freely contribute ideas regardless of their uncertainty and failure, which encourages divergent thinking. The design team as a group must clearly define the design problem objective and its constraints before starting the AHP process. Thus, AHP imposes the Closed-World Condition (CWC) at the beginning of the design process, which is mentioned in the literature of Advanced Systematic Inventive Thinking (ASIT) as the sufficient condition for creativity.[17] The structured AHP will then be able to facilitate the convergent thinking to arrive at a final design through aggregated group ranking. Davies argued that AHP is a preferable decision-making support system over others because it can generate advertising creativity.[18] He attributed the success of AHP to its "elaborate model structuring, the blending of rational and intuitive thoughts, assessment of judgment consistency and facilities to encourage learning". AHP enables advertising managers to work closely and harmonically in a structured environment that encourages new ideas and learning. In short, AHP possesses many positive attributes of a creative process that encourages teamwork, divergent-convergent thinking, problem definition and problem solving. AHP itself does not generate a creative design, but serves as a guidance to facilitate a creative process.

The structured AHP process reviewed above falls nicely into the model of the Concept-Knowledge (C-K) design theory.[19] The C-K theory, unlike other design theories, is used to evaluate a design process, not its outcome. The C-K theory takes creativity into consideration when it is applied to analyze a design process. A creative design must be initiated from a new concept which is evolved or generated from an existing one. The new knowledge or technology must be collected and developed in order to evaluate and analyze the new concept and convert it into a useful, physical product. Specifically, the C-K theory defines the design process in two spaces – the concept space and the knowledge space. The knowledge space is a collection of propositions supported by logics, while the concept space is a collection of those not supported by any logic found in the knowledge space. A creative design process modeled by the C-K theory consists of four operations: Knowledge to Concept, Concept to New Concept, Knowledge to New Knowledge, and New Knowledge to New Concept as shown in Figure 1. Any new design is generated through these four operations. The C-K theory proves that the necessary condition for a design process to be creative is to have C-expansion and K-expansion.

That is, new logic must be discovered or utilized in order to validate a new concept, while a new concept may be born out of new knowledge in order to have a creative design.

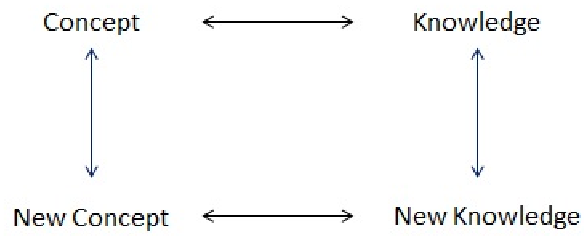

Figure 1. The Concept and the Knowledge Spaces in the C-K Theory

According to the C-K theory, the availability of new concept and new knowledge are the necessary conditions to generate a creative design. Divergent thinking is indeed an important attribute to generate a new concept, while convergent thinking searches ways to validate the new concept and to convert it into a useful product. The first three phases mentioned by Baillie[1] and Liu and Schonwetter[4], i.e. preparation, generation and incubation, are processes to generate a new concept, while the last two phases, verification and evaluation, are processes to carry out new knowledge.

5. Review of Other Creativity Processes

Efforts have been made to develop systematic tools in the industry to assist a creative design process. These tools are broadly categorized into two groups: concept-based and knowledge-based.[11,20] TRIZ and ASIT are typical examples of concept-based tools.[21] TRIZ is the Russian acronym for the "Theory of Inventive Problem Solving". TRIZ was developed by a Russian scientist, G. S. Altshuller and his colleagues. TRIZ hypothesized that the solution of any given problem or one similar to it has already be done. Creativity is how to find that solution and adapt it to the specific problem. After reviewing 2.5 million patents from 1946 to 1985, Altshuller and his colleagues found patterns that led to the breakthrough solutions to given problems. These patterns were summarized into 40 inventive principles for problem solving, the separation principles, laws of technical evolution and technology forecasting and 76 standard solutions. Advanced Systematic Inventive Thinking (ASIT) is a creative thinking method derived from TRIZ by R. Horowitz in 1999.[17] ASIT simplified TRIZ's principles into one condition, one principle and 5 operations to generate a new, creative design. The Closed World Condition (CWC) defines the use of existing resources to find the solution once the problem is defined. The Achieving Qualitative Change Principle (QC) requires that the contradiction between demand and solution is resolved by making the obstacle of finding a solution irrelevant. The five operations of ASIT are Unification, Multiplication, Division, Breaking Symmetry and Object Removal:

Unification – create a new use of the existing components or objects
Multiplication – make a slight modification of the existing objects in the current system
Division – divide objects into parts

Breaking Symmetry – turn a symmetric situation into a non-symmetric situation
Object removal – reduce the number of objects

How and why ASIT produces a creative design have been confirmed and explained by modeling its logics in C-K spaces.[19] ASIT has been used in the industry to produce creative designs. In fact, the creativity of the Coloplast design team is a successful application of ASIT.[22] The design team should have domain knowledge in order to clearly define the constraints. The constraints described here are related to the performance requirements which can be expressed in terms of the objectives and the constraints of the design problem. The constraints are called "hard" if they are not easy to define or measure, "flexible" if they are changeable, "important" if they are "must haves" and "formal" if they are required by regulation. The constraints control and stimulate the creative process through the partition, the removal, the introduction and the revision of a constraint or constraints in a design process. The partition of a constraint helps the design team to box in the non-flexible part of the constraint and to focus on that which can be changed. The introduction of a new constraint sometimes helps the team to investigate the consequence of having a constraint which may lead to a new solution that overcomes the initial constraint. Often the team can quickly identify the most crucial constraint which requires the primary focus. The constraints play the role of the closed world condition (CWC) of the ASIT and the most crucial constraint is the main problem factor. The constraint partition is an act of division and multiplication. The constraint revision leads to unification and the constraint introduction may break symmetry.

Both TRIZ and ASIT have been criticized due to the significant time required to master the methods. Furthermore, a sophisticated product which requires investigation will not be easily generated by either TRIZ or ASIT. On the other hand, knowledge-based creative design tools aim to accumulate, formulate and manage knowledge so that the knowledge is easily extracted and clearly presented for problem solving. Data mining, global optimization, artificial intelligence, machine learning and visualization are all the core ingredients of many knowledge-based creative design tools.

Song et al developed an innovative, system design tool that supports a design process made of Morphology Analysis (MA) and TRIZ-based technology.[23] The former is used for analyzing and decomposing system functions to start the proposed, system design process. It is followed by using the latter to map out and evaluate technology evolution opportunities. In the final step, the Su-Field analysis in TRIZ is used to identify the necessary technology to realize a new system design. The proposed process follows the C-K theory in which the MA defines and explores the function requirements for a new design task. TRIZ is used to create new concepts and transform them to be solved technically.

The systematic tools reviewed here are fundamentally different from the AHP-based creative design tool proposed herein. The former place their emphases on manipulation and management of ideas and knowledge, while the proposed tool focuses on openness and diversity among team members in a structured process to assist the creative design process. Both approaches are complementary to each other, as is shown through the case studies evaluated in this feasibility study.

6. An AHP-based Creativity Process

Realizing the benefits and potentials of AHP to creative design, the investigators have developed a basic 6-step AHP-based creativity process, shown in Table 2, to teach design creativity to undergraduate engineering students.

Table 2. The Proposed AHP-based Creativity Process

Step 1. Knowledge Collection The mission requirements for the targeted design question will be introduced to the class. The reference materials of the domain knowledge and technology should be made available to students.
Step 2. Concept Generation Students are encouraged to discuss as a team and propose possible design concepts to fulfill the mission requirements. Students are encouraged to record their discussions and make the sketches of the proposed designs.
Step 3. Criteria Generation Possible criteria used to weight and select the best design are solicited and discussed in the classroom. The criteria are categorized and structured in a hierarchical level. Each design team is asked to fill out pairwise comparison tables for the selected criteria. The method of right eigenvector or geometric mean of the AHP is used to find the weighting coefficients of all evaluation criteria. The results are made available to the entire classroom.
Step 4. Design Generation Students are asked to consolidate and strengthen their design concepts in accordance with the weighting of the evaluation criteria so as to gain a favorable evaluation for their final design.
Step 5. Design Evaluation Each team is required to present its design to the entire class. Each team is also asked to make pairwise comparison of all presented designs based upon the evaluation criteria. The AHP will then be used to rank the presented designs. The results will be made available to the entire class, which indicate the weakness and the strength of each design in relation to others, based upon the weighted evaluation criteria.
Step 6. Design Refinement It is possible to repeat Steps 1 to 5 to further improve the presented designs based upon the new knowledge about the weakness and the strength of each design.

The proposed AHP-based creativity process can be modeled in terms of C-K constructs so as to prove its validity, as shown in Table 3.

Table 3. The C-K Constructs of the Proposed AHP-based Creativity Process

AHP-based Creativity Process	***C-K Constructs***	***AHP Operations***
Knowledge Collection (Class Activity)	K and C spaces	
Concept Generation (Team Activity)	C to expanded C; K to expanded K (problem finding, divergent thinking)	
Criteria Generation (Class Activity)		Pairwise Comparison, Hierarchical Levels
Design Generation (Team Activity)	expanded C to expanded K (problem solving, convergent thinking)	
Design Evaluation (Class Activity)		Pairwise Comparison, Decision Making
Design Refinement (Team Activity)	Restart the process with newly expanded K and C spaces that cover the entire collection of designs.	

7. Case Studies

In this initial investigation, the AHP-based design process has been incorporated into three case studies: a senior capstone design project team, a module in a freshmen explore to engineering class and a sophomore/junior web design class. These case studies represent three different scenarios. In Case Study 1, the capstone design project team involved only a small group of four senior students. In Case Study 2, the entire freshmen class was dedicated to the design project for a period of 6 hours in 3 weeks. In Case Study 3, the AHP-based design process was used to assist students in an internet programming class to create a business website as their final class project. These case studies serve two purposes: first, to validate that the proposed AHP-based process can lead to creative design; and two, to investigate the effectiveness in teaching the proposed AHP-based process for creative design. The details of the case studies and the lessons learned are summarized below.

7.1 Case Study 1: Senior Design Project Team on ASV Design

The Autonomous Surface Vehicle (ASV) team recently applied the proposed AHP-based creativity process to design a new ASV hull to enter the robot-boat competition sponsored by the Association for Unmanned Vehicle Systems International (AUVSI). The team is made of four senior students in the Mechanical and Aerospace Engineering Department. The detailed implementation of the AHP-based process is given below in Table 4. The classical AHP was introduced to the team at the beginning of the design process.

Table 4. Applying the AHP-based Creative Process to ASV Design

Step 1. Knowledge Collection   The existing ASV design was discussed in the team meeting. Its strength and the weakness were discussed. The existing ASV's designed by other universities were also reviewed in the meeting. All of the reference materials were made available to the students. The goal of the new boat hull design is to increase the upper deck space in order to house additional hardware. The boat, however has to be limited by 110 lbs in weight and 6-ft by 3-ft by 3-ft in size. Members are encouraged to develop their own design concepts.
Step 2. Concept Generation   Members of the team have developed several new boat concepts. However, after two months of effort, the team agreed to use the team captain's concept design as the new boat hull.
Step 3. Criteria Generation   Members of the team were informed the first time to propose evaluation criteria to select the best boat hull design. The proposed evaluation criteria were collected and consolidated into two hierarchical levels with 8 upper level criteria. Students were then asked to individually submit their pairwise comparison tables to weight the selected criteria. Each pairwise comparison table went through consistency check. The consistency check was performed by the instructor to all comparison tables. The evaluator was asked to re-evaluate any comparison table whose CR is greater than 0.1. The final weighting factors are listed in Table 5.
Step 4. Design Generation   Each student member was required to revisit his conceptual design and modify it according to the finalized evaluation criteria before submission, with the recognition that some criteria would be weighted more heavily. The collected designs were reviewed and discussed openly in the classroom and consolidated into three distinct designs, one of which was the design produced in Step 2. The proposed designs are presented in Appendix I.
Step 5. Design Evaluation   Each team member was then required to conduct design evaluation of the designs and submit his comparison tables. The AHP was then used to weight and evaluate the design alternatives. The results are listed in Table 6. The strengths and weaknesses of each design alternatives were readily apparent from the AHP criterion after scoring. Brief descriptions of the final designs are given in Appendix I. Design Alternative 3 shown in Figs. A.5 and A.6 is the control design produced in Step 2, while Design Alternatives 1 shown in Figs. A.1 and A.2 is the

best design developed using the proposed AHP-design process.
Step 6. Design Refinement It is possible to repeat Steps 1 to 5 to further improve the presented designs based upon the new knowledge about the weakness and the strength of each design.

Table 5. AHP Results for Design Criteria Evaluation

ID	Top-Level Criteria	Weights	Lower-Level Criteria	Weights
1	*Weight*	(0.1953)		
2	*Surface Area*	0.1939)		
3	*Technical Readiness Level(TRL)*	(0.1376)	*Installation Readiness* *Cost*	(0.75) (0.25)
4	*Integration Readiness Level(IRL)*	(0.1199)	*Power Supply* *Wiring* *Installation*	(0.4126) (0.2599) (0.3275)
5	*Environmental Interference*	(0.0595)	*Communication Interference* *Temperature Sensitivity* *Water Tightness*	(0.3956) (0.1323) (0.4566)
6	*Reliability*	(0.1766)	*Redundancy* *Ease of Repair* *Number of Parts*	(0.3039) (0.4426) (0.1942)
7	*Overall Cost*	(0.0601)		
8	*Portability*	0.0557)	*Transportability* *Launchability*	(0.3433) (0.6389)

Table 6. AHP Score for Design Alternatives

Design Alternatives	AHP Score	Strengths	Weaknesses
1	0.3819	Weight / TRL / Cost	Reliability
2	0.3702	Surface Area / IRL / Environmental Impact	Weight Cost
3	0.2478	Weight / Portability / Cost Cost	Surface Area

Case Study 1: Lessons Learned

The proposed AHP-based design process had a definite effect on the design development and on the final design selection. The AHP-based design process ranked the unguided design alternative 3 the lowest when compared to the other options. Also, the other design alternatives had some unorthodox features that resulted from creative attempts to score high on the AHP criteria. The ASV team members all agreed in a post-design survey that the use of the proposed AHP-based process helped to focus and guide the development of their design concept generation. Additionally, the involvement of the ASV team members in the criteria development stage of AHP resulted in a deeper understanding of the design requirements.

AHP includes a method for determining the consistency of the pairwise comparisons. The ASV team found this to be an area of concern in the application of the process, and had to revise the pairwise comparisons several times to achieve acceptable consistency. This suggests that AHP can be somewhat subjective. Additionally, it was found during the criterion weighting exercise that some experience was necessary to accurately weight the criteria. Due to the qualitative nature of some of the criteria, a sensitivity analysis should be performed to further verify the results.

Step 6 of the proposed AHP-based design method could be applied to further optimize the final design. Table 6 shows the AHP score for each of the three design alternatives. Design alternative 1 scored the highest. An advantage of the AHP-based design approach is that it highlights the weakness of the alternative, the reliability. Looking closely at the reliability criteria in Table 5, this would include the number of parts, the redundancy, and the ease of repair. By incorporating Step 6 into the proposed AHP-based design method, design alternative 1 could be further refined to reduce the impact of these design weaknesses, thereby increasing the AHP score and resulting in an optimized design. This last step in the process helps students to understand the importance of focusing their attention and resources on improving an already desirable solution.

In short, this particular exercise supported the notion that the proposed AHP-based design process is a valid approach for creative design. The addition of Step 6 to the process would be helpful to further improve the design. The team members should have sufficient experience and knowledge to make reliable pairwise comparisons. The consistency and sensitivity checks make the AHP process somewhat burdensome, but the outcome of these checks further strengthen the process and enhance the final product.

7.2 Case Study 2: A Module for Exploratory Freshmen Engineering Class

All engineering freshmen at ODU are required to take this course, regardless of their majors. The class consists of 5 modules taught by faculty from 5 different engineering departments. Each module covers a three-week period for 2 hours of lecture time per week. The proposed AHP-based design process was implemented in one class module. 26 students in total were enrolled in the class. The class was randomly grouped into 7 teams, up to 4 students per team, and tasked to design a robot boat. The class activities are listed in Table 7. The final grades of the designs were assigned based upon their ranking and evaluation using the AHP-based process.

The class was required to develop a robot boat that can autonomously navigate through a channel of color buoys, identify the locations of challenge stations and perform the required missions. The latter includes stopping the sprinkle, pressing the specific button, finding and shorting at a target, landing on a platform to search and bring back a hockey puck, and gripping a flag at the rear of a moving vessel. Each team has to propose a navigation strategy and provide the list of hardware and software necessary to carry out the required missions.

The cost, ease of construction, speed of the boat, portability, and ability to meet the performance requirements were identified by the class as the four upper level evaluation criteria, as shown in Table 8. The final designs were grouped into three alternatives based upon their unique features. A brief description of each design can be found in Appendix 2. Design Alternative 1 is a refinement of the current design, while Design Alternatives 2 and 3 include novel concepts that were not found in the currently available designs. Design Alternative 2 proposes the use of a multi-purpose robotic arm to grip the hockey puck and the flag. Design Alternative 3 uses a quadrocopter for mapping and an amphibious jet ski with wheels to land on the floating platform to retrieve the hockey puck.

Table 7. Freshmen Class Activities and Assignments

Date	***Class Activities***		***AHP-based Process***
09/16	Lecture	Definition of design, Design formulation, Introduction to AHP, Navigation and Path-finding Requirement for ASV	Step 1
	Homework Assignment	Development of Concepts and Design Proposals	Step 2
10/23	Lecture	Presentation of Design Proposals Selection of Design Criteria; Construction of Hierarchical Levels	Step 3 Step 4
	Homework Assignment	The weighting coefficients of the design criteria to be posted on online. Finalization of the Proposed Designs	Step 5
10/30	Lecture	Class Presentation of the Final Designs Evaluation and Ranking of the Final Designs	Step 5

Table 8. Design Alternatives for Study Case 2

Design Alternatives	***Team ID***	***Key Features in the First Design Proposal after Step 2***	***Key Features in the Second Design Proposal after Step 5***	***Final Ranking after Weighted Evaluation***
1	1	Arm w/claw, tank wheel	Arm w/claw, tank wheel	**3**
	3	Car for puck retrieval	Car for puck retrieval	
	5	Arm w/claw; none for puck retrieval	Arm w/claw; car for puck retrieval	
2	4	None	Multipurpose Robotic Arm to grip the puck and the flag	**2**
	7	Using the same device to grip the puck and flag	Multipurpose Robotic Arm to grip the puck and flag	
3	2	Car	Boat equipped with deployable wheels	**1**
	6	Aerial device for mapping	Quadrocopter for mapping and jet ski with wheels to grip the puck	

Case Study 2: Lessons Learned

The class as a whole produced novel and useful designs through the AHP-based design process. Furthermore, the case study clearly showed that convergent thinking has been enforced from Step 2 to Step 5. However, the exercise revealed several concerns on the instructor's effectiveness in delivering the AHP-based process to the classroom, in its current format.

1. The design of an ASV requires a broad knowledge base. The six hours of the course module was not sufficient for the instructor to provide adequate domain knowledge for students to be creative. Students are unable to produce new concepts and new knowledge. As freshmen, the students' lack of expertise made it too challenging to tackle this problem. The instructor must build a strong knowledge base relevant to the problem in

order for the students to be successful. Alternatively, the instructor should select design problems that are suitable to the students' knowledge base to support the design. These design problems can be increasingly difficult as they are applied to first-year through fourth-year students.

2. Students complained about the tedious and time-consuming process to compute the priority vector (Eqn. 1). In the future, the investigators will develop Excel code using the AHP-based design process. The instructor will supply the code to the students along with examples on how to apply the code successfully.
3. Future offerings of this module will incorporate focused assessment on teaching effectiveness.

7.3 Case Study 3: A Web Design Class Project in Computer Science Department

The Advanced Internet Programming Class is offered by the Computer Science Department and open to all sophomores and juniors. A website design project is assigned to students near the end of the semester. The project requires students to design a comprehensive e-business website which should establish a business advertisement, enable online ordering and facilitate communication between customers and the business. The latter includes user registration, customer complaints, personal information, online payments, etc. The business can be of the student's choice with instructor approval. The construction of the website should use all of the following languages: HTML5, CSS, JavaScript and PHP with interactions to the MySQL database. The AHP-based process was embedded into the project schedule to enhance the web design creativity. The detailed milestones of the project were tabulated in Table 9. The project was assigned to students on Oct 23th and the final project report was due on December 4th. 12 students were enrolled and were divided into 6 teams, 2 in a team. The students were free to select their team members.

Case Study 3: Lessons Learned

This case study represents a fundamentally different application of the AHP-based design process from the previous two case studies as it required students to produce a tangible product, a functional website. The primary goal of the project is for students to practice and build confidence in Internet programming through designing and operating a real-world website. The investigators hoped to introduce the AHP-based design process to this project to further the creativity embedded in the web design. However the students struggled to learn enough domain knowledge and technology to make a working website. To take this matter into consideration, the instructor asked students to complete the initial phase of Design Generation (Step 4) ahead of Criteria Generation (Step 3) so that students could review and acquire the necessary knowledge to support their web page designs at the early stage of their design process. However, the instructors believe this adjustment came in too late - students had only 17 days to launch the final website after finishing the initial phase of Step 4. The websites produced at the end of the class had functional problems. Neither the results of the evaluation criteria nor the bonus points assigned to the project were a driving force to encourage students to think creatively. In the future, the investigators will revise the class project so that all teams are working on a website design for one company, with specific company requirements, to allow students to understand and apply the AHP-based design process to achieve creative web designs.

Table 9: Web Page Design Project

Milestones	***Activities***	***AHP process***
6 Nov.	• Select a business • Design interfaces of all web pages • Identify the required techniques to build the web pages	Step 1 Step 2
16 Nov	• Complete initial design of the web pages • Launch the web site	Step 4
18 Nov	• Determine and Rank Evaluation Criteria	Step 3
2 Dec	• Final web site launched	Step 4
4 Dec	• Project Presentations • Peer Evaluation and Ranking for bonus points	Step 5
6 Dec	• Update the web site for bonus points	Step 6

8. Concluding Remarks

This paper discussed the importance and the challenges of teaching design creativity to engineering students and conducted an initial look at the feasibility of employing the Analytic Hierarchy Process (AHP) to teach design creativity in undergraduate engineering classrooms. An AHP-based creativity process was proposed and implemented in three undergraduate classrooms. Based on this investigation, the authors concluded that future research efforts must include a clear distinction between the effectiveness of the proposed AHP-based process for creative production and the effectiveness of teaching the proposed AHP-based process in the classroom.

Since concept and knowledge expansion are the necessary conditions for an effective creative process, the users of the proposed AHP-based process should have sufficient expertise to generate and realize a design concept. The senior capstone project team members had the time and the experience to use the proposed AHP-based process effectively for creativity production. The six-hour module of the freshmen engineering exploration class had positive results but clearly indicated the need to ensure sufficient time and resources (knowledge base) for students to be active in pursuing creative designs. The third class, the advanced internet programming class, was a programming emphasized class. Students were all working on very diverse projects and struggling to make the code work, leaving little time to dedicate to achieving creative solutions. The lessons learned from this investigation can be summarized hereafter.

1. The proposed AHP-based process can be effective in creative production as supported by the C-K theory and clearly demonstrated by the first case study, the senior capstone project.
2. The instructor, who is the key in implementing and teaching the proposed AHP-based process in the classroom, should spend the time in the classroom and build up resources for students to acquire the domain knowledge and technology. A user friendly, Excel-based code should be developed to support AHP operations in the class. Excel is the code of choice as many students are familiar with it. Failure in doing so caused the delivery setback in the freshmen class and the internet programming class.
3. The instructor must confirm the design problem is relevant to the student knowledge base, or ensure there is sufficient time in the course to build the knowledge base. The

class that focuses on learning and utilizing the proposed AHP-based process should be accompanied with class projects requiring limited knowledge and technology.

4. It is desirable to teach and use the systematic inventive tools, such as ASIT, as part of the proposed AHP-based process, which can help in generating new concepts.
5. It is necessary to develop two distinct assessment methods: one for the effectiveness of the proposed AHP-based process for creative production and the other for teaching delivery effectiveness.

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Appendix I Final Designs in Case Study 1

Design Alternative 1

This design uses the existing deck, pontoons, and electrical box. The electrical box is moved to the position shown in Figures A.1 and A.2, where it replaces one of the pontoons. The result is decreased weight from the removal of the pontoon, with increased weight capacity due to both the loss of the pontoon weight and the additional buoyancy provided by the electrical box. In addition, the deck is then almost completely free of components and may be fully utilized.

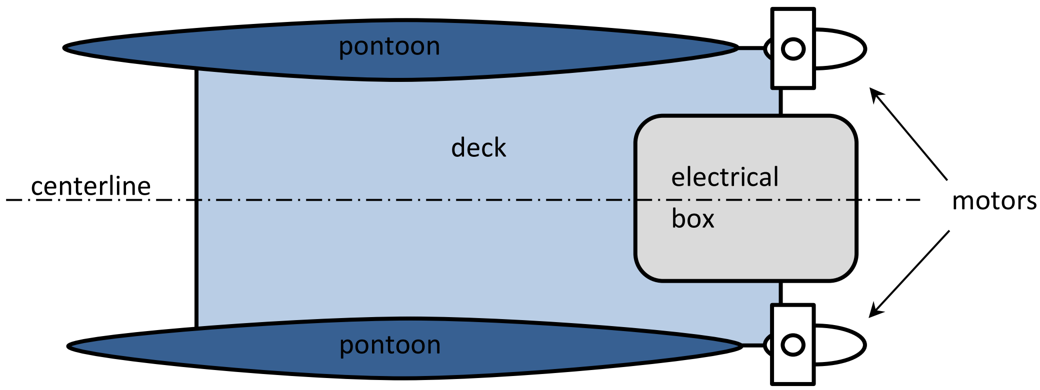

Figure A.1. Bottom view of proposed hull layout.

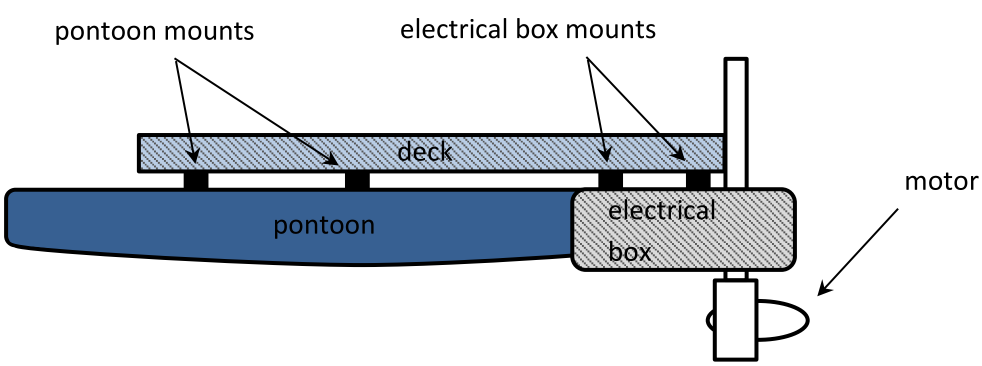

Figure A.2. Sectional side view of proposed hull layout. Section is taken along centerline.

Design Alternative 2

This design is composed of a large center hull and two smaller outrigger pontoons to either side of the main hull. The main hull will be a single pontoon of roughly 10 in diameter and 48 in long. The two outrigger pontoons will be the same pontoons as are used on the current ASV. The buoyant force is estimated to be 274 lbs. Figures A.3 and A.4 show the hull layout. All electronic components including the batteries will be housed inside the main hull. An access cover will be cut in the top of the main hull pontoon to provide access to the electronics housing area. A flat deck will cover the pontoons creating a large flat surface from which a deployment mechanism for the rover can be attached along with the GPS and kill switch modules.

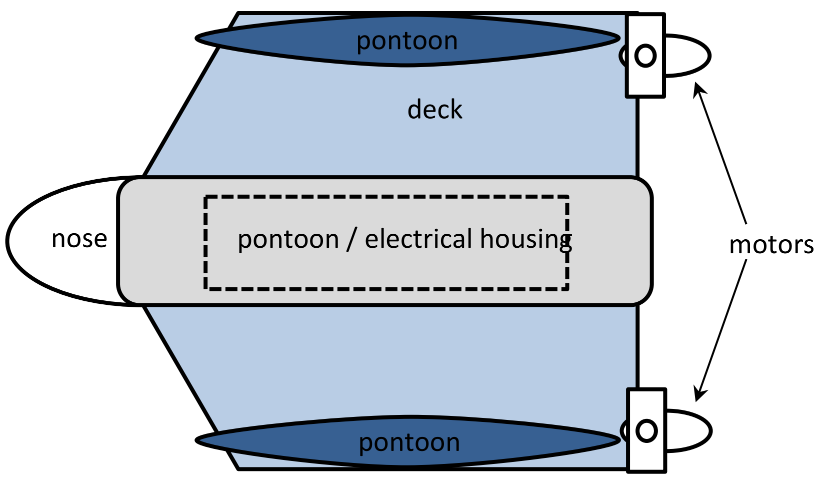

Figure A.3. Bottom view of proposed hull layout. Access to the electrical housing in the center pontoon is through an access panel on top of the deck (dashed line in figure).

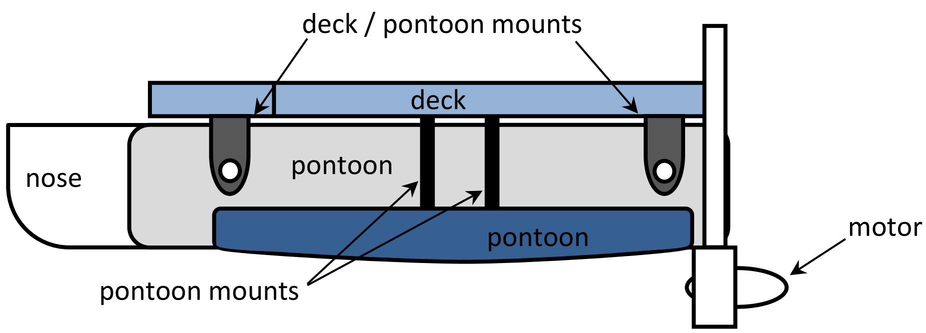

Figure A.4. Side view of proposed hull layout.

Design Alternative 3

Removal of the current electronics case will give more deck space and reduce weight. With two new larger pontoons, the electronics can be placed inside the pontoons. The electronics can be distributed inside the pontoons to allow for maximum stability. The buoyant force is estimated to be 87 lb. With only the necessary components on the deck, the deck will allow other large components to be mounted on top. The weight can further be reduced with the use of lightweight rails to support the deck, and custom motor mounts. Figures A.5 and A.6 show the proposed hull layout. Holes will be cut into the top surface of the pontoons to allow access to the electrical components. Wiring will be run through PVC tubes connecting the hulls.

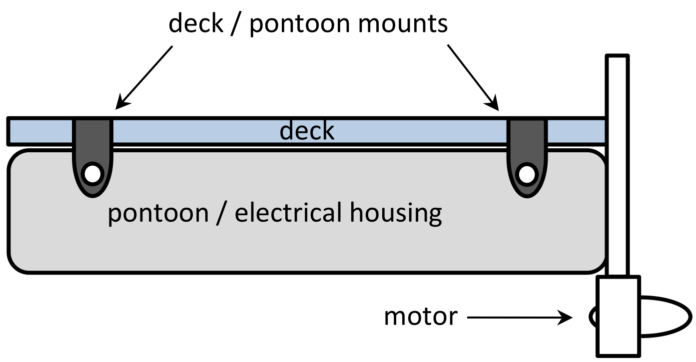

Figure A.5. Side view of proposed hull layout.

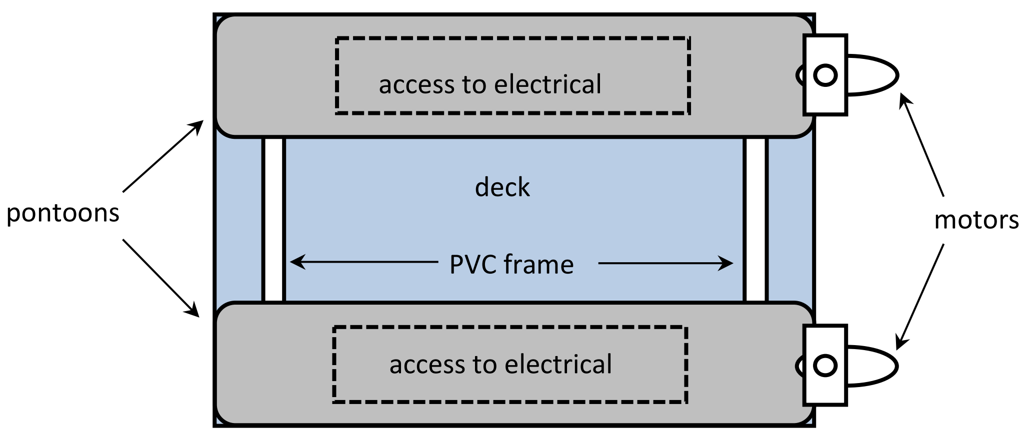

Figure A.6. Bottom view of proposed hull layout. Access to the electrical housing in the pontoons is through an access panel on top of the deck (dashed lines in figure).

Appendix II Final Designs in Case Study 2

Design Alternative I

Main Features: Car for gripping the hockey puck, robotic arm for pressing the button

Navigation
The boat will be equipped with a camera mounted on the front of the boat for recognition of colors, red, green, blue, yellow and purple. The distance between the boat and a buoy will be estimated based upon the size of the computer images of the buoys. LIDAR is also used for range finder. The combination of a camera, a LIDAR and the software of computer vision helps to navigate through the channel of buoys. The boat will install a GPS which reports the location of the boat. As a result, it can guide the boat to the challenge stations whose GPS locations are known. An IMU may be installed to track the motion and the yawing of the boat.

Challenge Stations
The boat will need to be waterproof for the sprinkler challenge. The motor and the propeller should allow the boat to maneuver easily. Sonar will be installed underneath the boat to detect the underwater buoy. A robotic arm will be built to press the right button closest to the underwater buoy to stop the sprinkler. The same robotic arm will be used later to grip the flag from the moving purple boat. A pressurized tube will be used to shoot the projectiles through the hoops. The boat will be equipped with a thermal sensor to detect the hot sign. An additional camera is needed to recognize the hand signs. A separate ground vehicle will be used to get out of the boat to retrieve the ball. A camera will be mounted on the vehicle to detect the ball. The vehicle will rely on the GPS of the boat to guide itself back to the boat.

Design Alternative II

Main Features: multipurpose robotic arm to grip the puck and to press the button

The proposed boat is equipped with a multi-purpose robotic arm and claws to grip the ball. Therefore, no ground vehicle is required.

Design Alternative III

Main Features: amphibious boat to run onto the floating platform to grip the puck, quadrocopter for mapping

The proposed boat will launch a quadrocopter to hover the field for mapping and location. The boat is modeled from a water ski jet. The boat is equipped with a set of retractable wheels make the boat an amphibious vehicle that can search and retrieve the ball on land.